

Comparing UK turkey production systems using analytical error propagation in uncertainty analysis

Ilkka Leinonen^{1,*}, Adrian G. Williams², Ilias Kyriazakis¹

¹ School of Agriculture, Food and Rural Development, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

² School of Applied Sciences, Cranfield University, Bedford, MK43 0AL, UK

* Corresponding author. E-mail: ilkka.leinonen@newcastle.ac.uk

ABSTRACT

The aim of this study was to quantify the environmental impacts per unit of live weight of the main UK turkey systems, namely stag and hen production with either controlled or natural ventilation. An LCA modeling framework, based on system approach and mechanistic sub-models was applied for this purpose. For the first time, detailed production data from the industry was used as input. The differences between the systems were analyzed using an analytical “top-down” method for uncertainty analysis, developed specifically for this study. The results show that there were only small, mainly non-significant differences in the impacts between the systems, affected mainly by their feed conversion ratio and slaughter weight. The novel uncertainty analysis method makes it possible to obtain exact quantification of the overall uncertainties of outputs of complex systems models without the need of time consuming and approximate Monte Carlo simulations.

Keywords: acidification potential, eutrophication potential, global warming potential, turkey production, uncertainty analysis

1. Introduction

According to Defra (2011), the UK turkey production in 2010 was 162 thousand tons carcass weight, which is over 10% of the total UK poultry meat production. Despite the importance of turkey systems and their potential contribution to the overall environmental consequences of livestock production, the environmental impacts of turkey production have so far only been analyzed using generic UK data (Williams et al. 2006). In order to quantify the current impacts of the main turkey systems, and to find ways to improve their environmental friendliness, detailed production data from the main turkey production companies is required, combined with a systematic assessment methods, such as agricultural LCA.

In earlier studies (Leinonen et al. 2012a; b; Williams et al. 2006), a systems approach-based modeling framework was developed to quantify the environmental impacts of poultry systems. As an essential part of this framework, a method for uncertainty analysis was also developed, in order to make statistical comparisons between the systems under consideration. In these studies, the uncertainty was quantified using Monte Carlo simulations, which is a common practice in agricultural LCA. However, the problem with such an approach is that it requires a lot of computing power, it is time consuming, and the output is only an approximation, the accuracy of which depends on the number of Monte Carlo runs used. Therefore, it is quite clear that there is a need for a more straightforward, preferably analytical method for quantifying the uncertainty in agricultural LCA studies.

The aim of the current study was to apply the LCA method, “from cradle to gate” to quantify and compare the environmental burdens of the main production systems in UK, namely 1) Stags (males) with controlled ventilation, 2) Hens (females) with controlled ventilation, 3) Stags with natural ventilation, and 4) Hens with natural ventilation. Another aim was to develop a novel analytical method for uncertainty analysis, which would allow exact quantification of the system uncertainties, without time consuming Monte Carlo simulations which could give only an approximate solution.

2. Methods

2.1. Systems approach and the data

The general approach taken in the current study was with systems modeling of production. This included structural models of the industry, process models and simulation models that were unified in the systems approach so that changes in one area caused consistent interactions elsewhere. This approach was applied to both feed crop and animal production. The systems modeled in this study included crop production, non-crop nutrient

production, feed processing, breeding, turkey brooding, turkey finishing and manure and general waste management, following the overall principles presented by Williams et al. (2006) and Leinonen et al. (2012a;b).

The production systems in this study were considered to represent typical mainstream UK turkey production, i.e. stags and hens, both with either controlled or natural ventilation. The farm energy consumption for heating, lighting, ventilation and feeding was based on average data from typical farms as provided by the main UK turkey production companies. Information about the type and amount of bedding and other material use was also obtained from the industry. The bird performance and production data, including the length of the production cycle, stocking density, final weight, feed intake and mortality came from actual farm data provided by the industry. The main production figures for different systems are presented in Table 1. Additional data, such as life cycle inventories (LCI) of agricultural buildings and machinery, came from Williams et al. (2006). The baseline diets representative of those used in the UK for each system were constructed using information provided by the turkey industry, and the environmental impacts arising from feed production were calculated based on the relative proportion of each ingredient in these diets.

Table 1. The average production figures for the main UK turkey systems considered in this study

System	Age at slaughter, days	Weight at slaughter, kg	Feed conversion ratio, kg feed/kg live weight
Stags, controlled ventilation ¹	133	15.2	3.1
Hens, controlled ventilation	95	7.3	2.8
Stags, natural ventilation	137	16.6	3.1
Hens, natural ventilation	90	6.7	2.6

¹In this system, the birds were predominantly males, but some farms with mixed flocks with small amount of females are also included.

2.2. The models

The structural model for turkey systems calculated all of the inputs required to produce the functional unit (1000 kg of live weight), allowing for breeding overheads, mortalities and productivity levels. It also calculated the outputs, both useful and unwanted. Changes in the proportion of any activity resulted in changes to the proportions of others in order to keep producing the desired amount of output. Establishing how much of each activity was required was found by solving linear equations that described the relationships that linked the activities together.

The model calculated the N, P and K contents of the manure according to the mass balance principle, i.e. the nutrients retained in the animal body were subtracted from the total amount of nutrients obtained from the feed. For the purpose of the study, it was assumed that all manure was transported for soil improvement.

A separate sub-model for arable production was used to quantify the environmental impacts of the main feed ingredients, with main features as in Williams et al. (2010). All major crops used for production of turkey feed were modeled. For the crops produced overseas (soya, palm oil) the production was modeled as closely as possible using local techniques, and transport burdens for importing were also included. The greenhouse gas emissions arising from land use change were taken into account according to the principles of the carbon footprinting method PAS 2050:2011 (BSI 2011).

A separate sub-model was also used for manure and the nutrient cycle. In the model, the main nutrients that were applied to the soil in manure were accounted for as either crop products or as losses to the environment. N was explicitly partitioned into readily plant available and slow-release organic N. The crop yield response was compared with that from manufactured N and the benefits were credited to poultry by offsetting the need to apply fertilizers to winter wheat as described by Sandars et al. (2003) and implemented by Williams et al. (2006). Losses as nitrate or by denitrification were calculated on a long term basis.

2.3. Environmental impacts

Emissions to the environment were aggregated into environmentally functional groups as follows. Global Warming Potential (GWP) was calculated using a timescale of 100 years. The main sources of GWP in turkey industry are carbon dioxide (CO₂) from fossil fuel, nitrous oxide (N₂O) and methane (CH₄). GWP was quantified as CO₂ equivalent: with a 100 year timescale 1 kg CH₄ and N₂O are equivalent to 25 and 298 kg CO₂ respectively (Foster et al. 2007).

Eutrophication Potential (EP) was calculated using the method of the Institute of Environmental Sciences (CML) at Leiden University (<http://www.leidenuniv.nl/interfac/cml/ssp/index.html>). The main sources in turkey production are nitrate (NO₃⁻) and phosphate (PO₄³⁻) leaching to water and ammonia (NH₃) emissions to air. EP was quantified in terms of phosphate equivalents: 1 kg NO₃-N and NH₃-N are equivalent to 0.44 and 0.43 kg PO₄³⁻, respectively.

Acidification Potential (AP) was also calculated using the method of the Institute of Environmental Sciences (CML) at Leiden University. The main source in turkey industry is ammonia emissions, together with sulfur dioxide (SO₂) from fossil fuel combustion. Ammonia contributes to AP despite being alkaline; when emitted into the atmosphere, it is oxidized to nitric acid. AP was quantified in terms of SO₂ equivalents: 1 kg NH₃-N is equivalent to 2.3 kg SO₂.

Primary Energy Use included all the energy needed for extraction and supply of energy carriers.

2.4. Breakdown of the environmental impacts

The results were broken down by the following material (and energy) flow categories (or sub-systems) to demonstrate their relative contribution to the overall impacts:

1) Feed: production of crops and additives, feed processing and transport. This category also includes the water consumed during housing.

2) Farm Electricity: direct electricity consumption at the farms (breeding, brooding and finishing) and hatcheries, not including feed production, processing and transport.

3) Farm Gas and Oil: direct fuel consumption at the farms and hatcheries, not including feed production, processing and transport.

4) Housing: direct emissions of NH₃, CH₄ and N₂O from housing and burdens from construction of farm buildings and vehicles, not including buildings and vehicles used in feed production, processing and transport of ingredients.

5) Manure and Bedding: emissions from manure storage and field spreading and the production of the bedding. This category also includes credits from replacing synthetic fertilizers. It does not include direct emissions of NH₃, CH₄ and N₂O from housing.

2.5. Uncertainty analysis

The uncertainties in the input variables can be divided into two groups, namely “alpha” and “beta” uncertainties, according to a concept first presented by Wiltshire et al. (2009) and Chatterton et al. (2010), and later applied for LCA for poultry production by Leinonen et al. (2012a). Alpha uncertainties can be considered to vary between systems, and therefore they should be taken into account in statistical analyses of the differences between the systems. For example, variation between farms in production, feed intake and energy use figures can all be considered to represent alpha uncertainties. In contrast, beta uncertainties are considered to be similar between the systems, and, following the principles of earlier studies, they were assumed to have no effect on the statistical comparison between the systems (Wiltshire et al. 2009; Chatterton et al. 2010; Leinonen et al. 2012a). Examples of the beta uncertainties are the emission factor for N₂O from manure, conversion factor from electricity to primary energy, and in general errors related to the modeling framework. In this study, the aim was to compare statistically the differences between production systems, and therefore only the alpha uncertainties are considered in the following.

To quantify the overall alpha uncertainty of the outputs of the LCA model, a novel, analytical “top-down” approach was developed for this study. In this analysis, the outputs (i.e. each category of environmental impacts per functional unit) were divided into separate components based on their sources, e.g. feed production, manure management and on-farm electricity use. Each component (*i*) was then expressed as a simplified function, and the total emissions of the system were calculated as their sum. For example for GWP, this can be expressed as:

$$GWP = \sum EC_i \times Activity_i \quad \text{Eq. 1}$$

where *Activity_i* represents for example material or energy use per FU, and the “emission coefficient” *EC_i* is the quantity of greenhouse gas (GHG) emissions per unit of activity. Depending on the context, the emission coeffi-

cient can be a simple emission factor, result of a complex function or outcome of the LCA model. In some cases, the EC_i can be considered to have both alpha and beta uncertainties, and in some other cases beta uncertainties only. If the latter option is true, then the uncertainty of the emissions coefficient can be ignored in the uncertainty analysis.

For example in the case of GWP, the emissions arising from feed production and manure management can be expressed with a simple linear function where the “activity” represents the feed consumption per functional unit, i.e. the feed conversion ratio (FCR):

$$F + M = a + (EC_f + EC_m) \times FCR \quad \text{Eq. 2}$$

where F and M are the GHG emissions from feed production and manure, respectively, EC_f and EC_m are the emissions coefficients (calculated by fitting the above equation to the outputs of the full LCA model) for feed and manure, respectively, and FCR is the average feed conversion ratio, i.e. the mass of feed divided by the liveweight gain. The constant a , which was also calculated from the model outputs, is needed in the equation because the manure emissions are not directly proportional to the feed intake. Instead, it can be considered that there is a theoretical, (very low) level of feed intake where the nutrient intake equals the nutrient retention (assuming that this remains unchanged), and as a result, the emissions from manure are zero at that point.

Now the alpha uncertainty for the GHG emissions from feed production and manure management can be quantified using a general uncertainty propagation rule (e.g. Taylor 1996):

$$\left(\frac{\sigma_{F+M}}{F+M}\right)^2 = \left(\frac{\sigma_{EC_f}}{EC_f+EC_m}\right)^2 + \left(\frac{\sigma_{FCR}}{FCR}\right)^2 \quad \text{Eq. 3}$$

where σ_{F+M} is the alpha uncertainty (standard deviation) of the combined feed and manure emissions, σ_{EC_f} the alpha uncertainty of the feed production emissions (quantified from the output of the crop production sub-model), and σ_{FCR} the variation in the feed conversion ratio, quantified directly from the data provided by the turkey industry. The alpha uncertainty for the manure emission coefficient was considered to be zero and therefore it does not appear in the equation.

For the other GHG emissions, the emissions from direct farm electricity use (E) can be expressed simply as:

$$E = EC_e \times Eu \quad \text{Eq. 4}$$

where EC_e is the emission coefficient for electricity and Eu is the average farm electricity use per functional unit. The emissions for farm gas consumption (G), or other fuel consumption where applicable, can be expressed exactly in the same way.

Again, the alpha uncertainty for the emissions from direct electricity use (and similarly for direct gas and other fuel use) can be quantified as:

$$\sigma_E^2 = EC_e^2 \times \sigma_{Eu}^2 \quad \text{Eq. 5}$$

where the variation in the electricity consumption per functional unit (σ_{Eu}) comes directly from the industry data.

The direct GHG emissions from housing (H) are mainly N_2O in turkey production, and they were not included in the manure emissions described above. Instead, the housing N_2O emissions were modeled separately based on the live weight and the duration of housing. Therefore, these emissions per live weight can be expressed as:

$$H = EC_h \times Age \quad \text{Eq. 6}$$

where Age is the average slaughter age of the birds. Now the alpha uncertainties for the housing emissions can be calculated as:

$$\sigma_H^2 = EC_h^2 \times \sigma_{Age}^2 \quad \text{Eq. 7}$$

where the variation of the slaughter age (σ_{Age}) comes directly from the industry data.

Finally, the overall alpha uncertainty for the total GHG emissions can be quantified as sum of the alpha uncertainties of the different components presented above:

$$\sigma_{GWP}^2 = \sigma_{F+M}^2 + \sigma_H^2 + \sigma_E^2 + \sigma_G^2 \quad \text{Eq. 8}$$

It should also be noted that when the uncertainty terms of the above equations are correlated, their covariance should also be taken into account in error propagation. However, in the case of the turkey emission model, most of the activities considered can be assumed to be independent from each other. The only exceptions are the slaughter age (used to model the emissions from housing) and the feed conversion ratio (feed and manure emissions). In theory, FCR should increase with the increasing age of the bird. However, in the data used in the present study, no consistent correlation between these variables was found within the systems, so the covariance between these variables was ignored in Eq. 8.

The uncertainties for other impact categories could be calculated mainly following the principles presented above. The main difference can be found in Eutrophication and Acidification Potentials, where the combined emission from feed production, housing and manure management can be expressed as a linear function of FCR. For example, for Eutrophication Potential this can be expressed as follows:

$$F + H + M = a + (EC_f + EC_h + EC_m) \times FCR \quad \text{Eq. 9}$$

where F , H and M are the components of Eutrophication potential related to feed production, housing and manure management, respectively, EC_f , EC_h and EC_m are the eutrophication emission coefficients for feed, housing and manure, respectively. The alpha uncertainty for the EP arising from these components can be then quantified as:

$$\left(\frac{\sigma_{F+H+M}}{F+H+M}\right)^2 = \left(\frac{\sigma_{EC_f}}{EC_f+EC_h+EC_m}\right)^2 + \left(\frac{\sigma_{FCR}}{FCR}\right)^2 \quad \text{Eq. 10}$$

Finally, a statistical analysis was conducted to evaluate the differences (at the $P < 0.05$ level) between the systems, based on the overall alpha uncertainties of each impact category, as described by Leinonen et al. (2012a).

3. Results

The environmental impacts of different turkey production systems, the contribution of different subsystems, and the alpha uncertainties of the impacts are presented in Figures 1-4. The results show that feed production, processing and transport was the main source of the impacts in the categories of Primary Energy Use and Global Warming Potential, while emissions from manure management had the biggest contribution to Eutrophication and Acidification Potentials. There was a lot of variation in the direct farm energy use (especially gas for heating) between the systems, but this had a relative small contribution to the overall impacts.

When the overall alpha uncertainties were applied in the statistical comparison between the systems, it was found that in most environmental impact categories there were generally no significant differences ($P < 0.05$) in the environmental impacts between the systems. A significant difference was found in Acidification Potential, where the stag system with controlled ventilation had a higher impact than the hen system with natural ventilation.

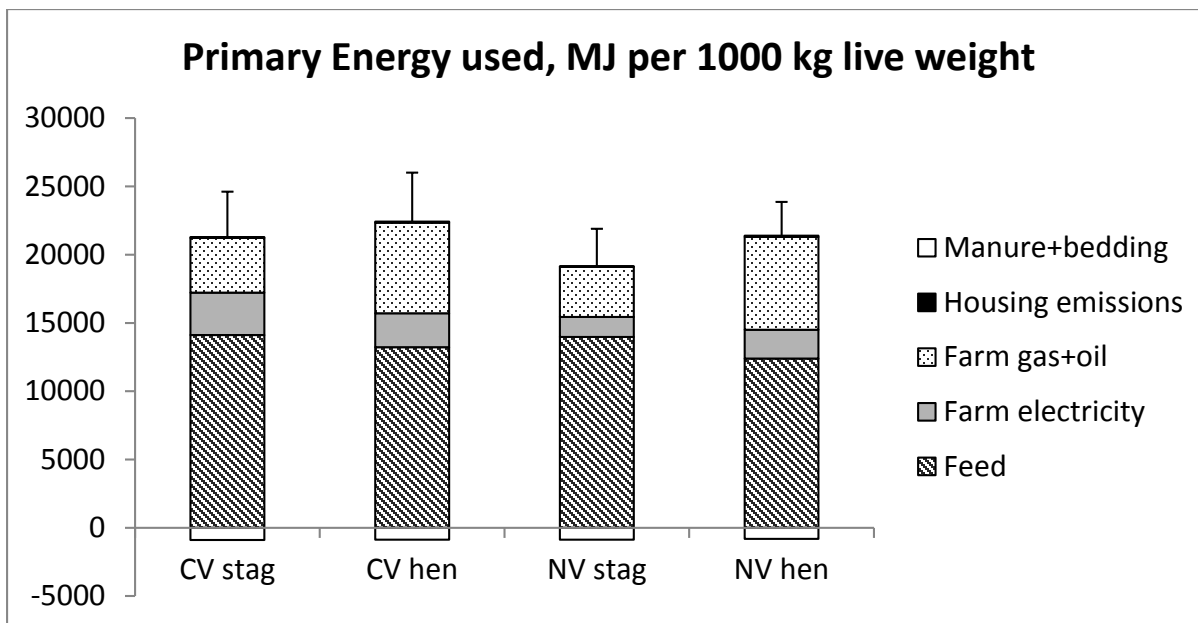


Figure 1. The Primary Energy Use of the four main UK turkey production systems. The error bars indicate standard deviations based on alpha uncertainties. CV=controlled ventilation, NV=natural ventilation.

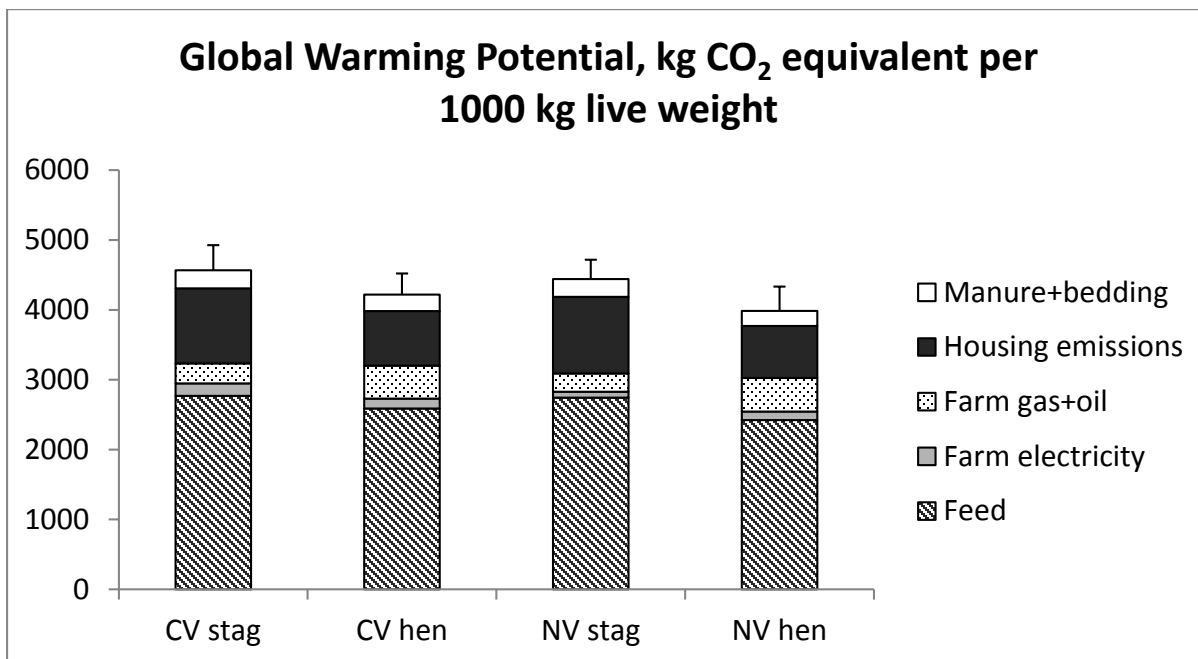


Figure 2. The Global Warming Potential of the four main UK turkey production systems. The error bars indicate standard deviations based on alpha uncertainties. CV = controlled ventilation, NV = natural ventilation.

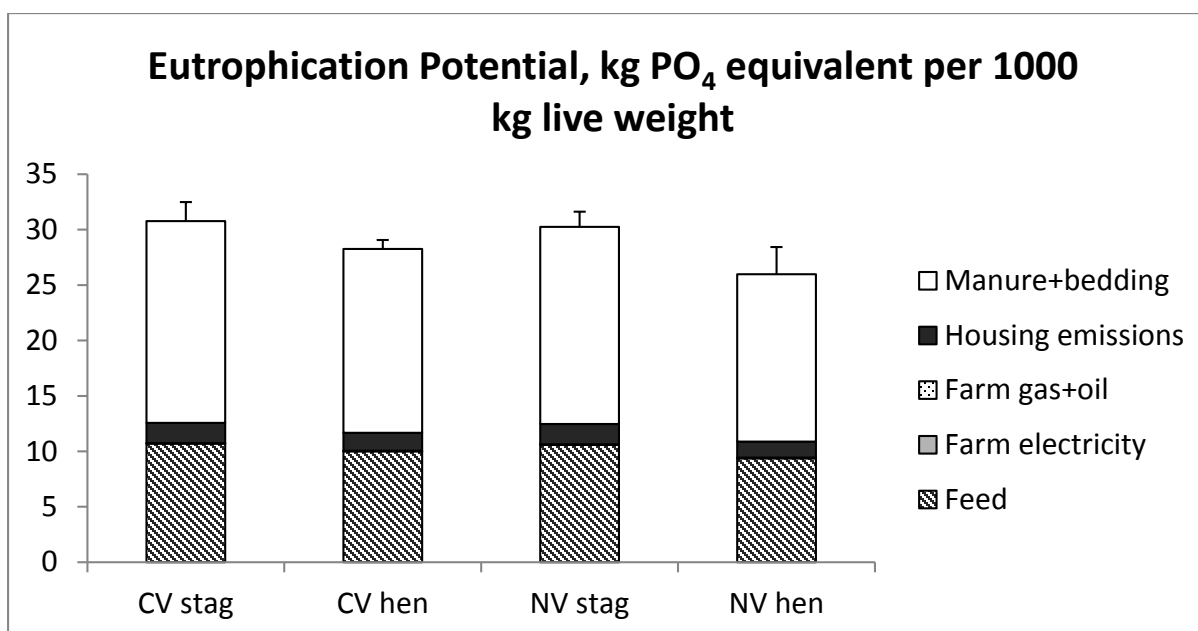


Figure 3. The Eutrophication Potential of the four main UK turkey production systems. The error bars indicate standard deviations based on alpha uncertainties. CV = controlled ventilation, NV = natural ventilation.

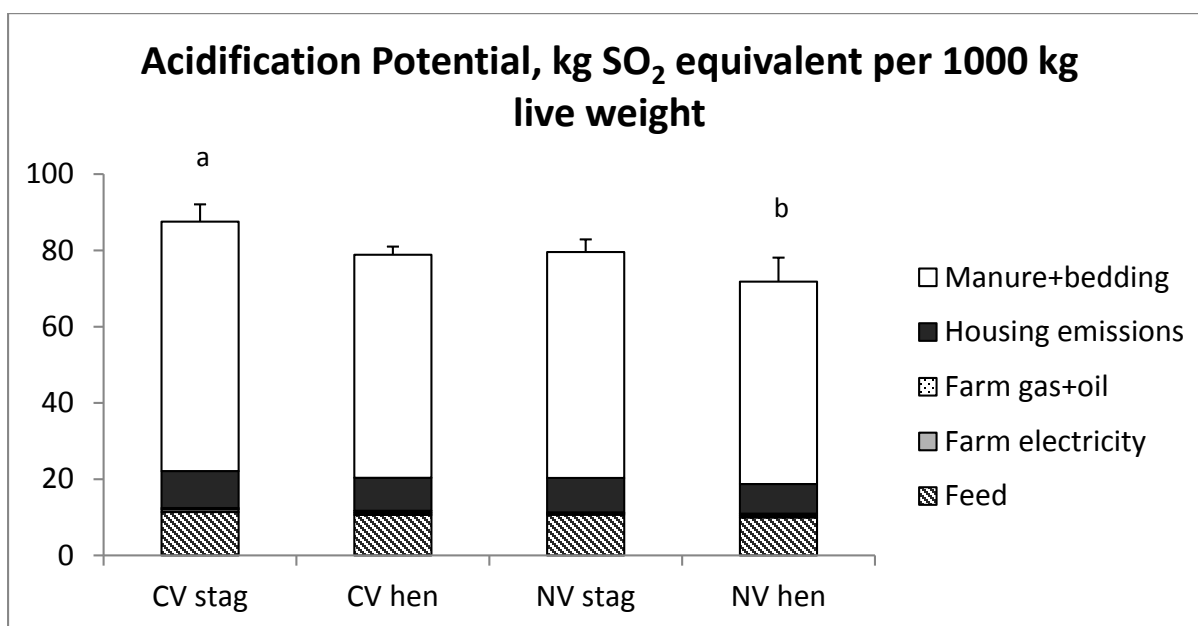


Figure 4. The Acidification Potential of the four main UK turkey production systems. The error bars indicate standard deviations based on alpha uncertainties. Different letters indicate a statistically significant ($P < 0.05$) difference between the systems. CV = controlled ventilation, NV = natural ventilation.

4. Discussion

There were only small (mainly non-significant) differences in the environmental impacts between UK turkey production systems, although some systematic trends occurred in certain sources of the impacts. These trends were mainly related to feed conversion ratio, which affected the emissions from feed production, housing and manure management. When the cycle length and the final body weight increase, an increase in the feed intake per unit of live weight is also expected, as the relative contribution of the energy required for maintenance, as opposed to growth, increases with the age of the bird. In the systems compared in this study, the hen systems al-

ways had a shorter cycle length and lower body weight compared to the stag systems. For this reason, the FCR was lower for hens than for stags, and the hen systems consequently tended to have lower impacts than the stag systems, especially for the Eutrophication and Acidification potentials.

In contrast, the farm energy consumption, especially heating gas, was higher per unit of live weight for the hen systems than for the stag systems. This difference was again related to lower slaughter weight of hens. Although it can be expected that for example the heating requirement would be similar per bird for stags and hens (as heating is mainly required for young birds only), hens produce less output (i.e. live weight) per bird, and therefore the impact per the functional unit is higher. Thus the better yield in the stag systems partially compensated the higher impacts related to poorer feed conversion in some impact categories. This leads to the observation that mitigation methods, such as using renewable energy for heating young birds would be more effective for hens than stags.

Any quantitative comparison between different systems is not feasible if the range of uncertainty in the results is not available. Despite this well-known fact, uncertainty analysis is not commonly applied in LCA studies for agricultural products. This omission can be partly explained by the extensive requirement of the data, in order to quantify the uncertainties in the input variables reliably. However, another reason might be the limitations of the chosen calculation method itself. Monte Carlo simulations are usually used in uncertainty analysis. Hence, the model used to quantify the environmental impacts is run several (generally thousands) times, and for each run, the input parameters are randomly sampled from a pre-determined distribution. Running of very complex models thousands of times requires a lot of computing power, and is also time consuming. Furthermore, the accuracy of the outputs of the Monte Carlo simulations (e.g. estimates for means or standard deviations) is directly dependent on the number of the runs. Therefore, the results of the Monte Carlo method can be seen as compromise between the reliability of the results and the use of computing power.

The problems related to the use Monte Carlo simulations in uncertainty analysis could be, in theory, avoided if the error propagation within the systems under consideration could be done analytically. The problem here is, however, that with very complex mathematical models, any analytical solution of uncertainty would require a huge amount of complicated calculations and in many cases could be impossible to perform. In the present study, a potential solution for this problem is presented by applying a “top-down” method, where the outputs of a complicated model are expressed with simple functions of the driving “Activity” variables. The contributions of all complicated sub-models are thus aggregated into simple emission coefficients. Quantifying the values of these coefficients would require running the model, in some cases several times (in the case of linear relationships, two model runs is enough), and then examining the broken-down outputs of the model to specify the relationships between the “Activities” and the “Emission coefficients”.

Despite its apparent complexity, the approach presented here can save much computing time compared to the thousands Monte Carlo runs, and if done correctly, it also provides an exact solution as opposite to the Monte Carlo approximations. A potential limitation of this analytical method is that in its current form it assumes that all uncertainties are normally distributed, while the Monte Carlo runs can utilize any type of distribution. Although the effect of this assumption was not examined in this study, it can be expected to have only minor effects on the results, keeping in mind that in many cases the actual form of the distribution of the input data may not be very well known anyway. So it can be expected that the overall principles of the analytical uncertainty analysis presented in this study would be applicable and beneficial in several applications of agricultural LCA, especially if their purpose is to perform quantitative comparison between separate systems or scenarios.

5. Conclusion

This study presents the environmental impacts of main UK turkey production systems, quantified for the first time using detailed industry data. Furthermore, a novel approach to uncertainty analysis is presented, where the “alpha” uncertainties, i.e. those varying between the systems under comparison are quantified analytically, thus saving time and computing power generally related to uncertainty analyses carried out with Monte Carlo simulations. The results of the system comparison show that in general there are only small, non-significant differences in the impacts between different systems. The main system-related variables affecting the impacts are the feed conversion ratio, which affects the food, housing and manure emissions, and the slaughter weight, affecting the energy use per functional unit.

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7. References

- BSI (2011) Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. PAS 2050:2011. <http://www.bsigroup.com/Standards-and-Publications/How-we-can-help-you/Professional-Standards-Service/PAS-2050/>
- Chatterton J, Bellamy P, Audsley E, Williams AG (2010). Demonstrating significant differences in carbon-footprinting, despite N₂O. Proc. LCAfood 2010. VII. Int. Conf. Life Cycle Assessment in the Agri-food Sector, Bari. <http://www.lcafood2010.uniba.it/>
- Defra (2011) Poultry and Poultry Meat Statistics. Department for Environment, Food and Rural Affairs. <http://archive.defra.gov.uk/evidence/statistics/foodfarm/food/poultry/documents/ppntc.pdf>
- Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007). Changes in atmospheric constituents and in radiative forcing. In: Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M, Miller, HL (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Leinonen I, Williams AG, Wiseman J, Guy J, Kyriazakis I (2012a) Predicting the environmental impacts of chicken systems in the UK through a Life Cycle Assessment: broiler production systems. *Poult Sci* 91:8-25
- Leinonen I, Williams AG, Wiseman J, Guy J, Kyriazakis I (2012b) Predicting the environmental impacts of chicken systems in the UK through a Life Cycle Assessment: egg production systems. *Poult Sci* 91:26-40
- Leinonen I, Williams AG, Waller AH, Kyriazakis I (2013) The potential to reduce environmental impacts of poultry production systems by including alternative protein crops in the diet: a quantitative comparison with uncertainty analysis. *Agr Syst* 121:33-42
- Sandars DL, Audsley E, Canete C, Cumby TR, Scotford IM, Williams AG (2003) Environmental benefits of livestock manure management practices and technology by Life Cycle Assessment. *Biosyst Eng* 84:267-281
- Taylor JR (1996). *An introduction to error analysis: the study of uncertainties in physical measurements*. University Science Books. 327 p.
- Williams AG, Audsley E, Sandars DL (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Main Report. Defra Research Project IS0205. <https://tinyurl.com/defra-is0205>
- Williams AG, Audsley E, Sandars DL (2010) Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. *The Int. J Life Cycle Assess.* 15: 855-868
- Wiltshire J, Tucker G, Williams AG, Foster C, Wynn S, Thorn R, Chadwick D (2009) Supplementary Technical Report to "Scenario building to test and inform the development of a BSI method for assessing GHG emissions from food". Technical Report in the Final Report to Defra on research project FO0404, London, UK. <http://preview.tinyurl.com/Fin-Rpt-FO0404>